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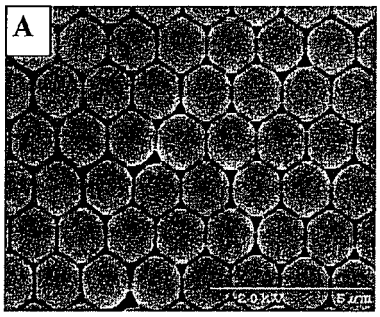
(54) Title: ATOM TRANSFER DISPERSION POLYMERIZATION

(57) Abstract: The present disclosure describes a two-step batch dispersion polymerization process for the preparation of substantially uniformed-sized functional (co)polymer particles. The first step of the process includes polymerizing at least one first radically (co)polymerizable monomer by a free radical polymerization process to form a (co)polymer in a stable colloidal dispersion and the second step includes polymerizing the at first radically (co)polymerizable monomer or an additional radically (co)polymerizable monomer in the stable colloidal dispersion by a living/controlled radical (co)polymerization process.

Fig. 2A



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TITLE

ATOM TRANSFER DISPERSION POLYMERIZATION

INVENTORS

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GOVERNMENT INTEREST

GRANT STATEMENT

Financial support was provided by the NSF through grants CHE-04-05627 and 05-49353. Therefore the Government of the United States has certain rights in this invention.

TECHNICAL FIELD OF THE INVENTION

The scope of a living/controlled radical polymerization, such as an atom transfer radical polymerization (ATRP) has been expanded to allow preparation of uniform-sized polymer beads with diameters between 0.1-15μm by defining conditions for an Atom Transfer Dispersion Polymerization (ATDP). A successful ATDP was accomplished by using a "two-stage" polymerization technique, in which the first stage involves a standard free radical polymerization and the second a living/controlled radical polymerization. Controlled addition of additional monomer, a second monomer, or a multifunctional monomer allows preparation of uniform size, functional, segmented, and/or crosslinked particles. Furthermore, use of a controlled/"living" radical polymerization allows retention of functionality suitable for post-polymerization modification of accessible particle surfaces.

BACKGROUND OF THE INVENTION

Polymer beads with substantially uniform sized diameters, between 0.5-10 μm, are finding an ever-increasing number of applications in coatings, electronics, microelectronics, biomedical, and information technology. Particle size control and narrow size distribution are key parameters for most of these applications. Several routes have been used to synthesize mono-disperse polymeric particles. One method is seeded suspension polymerization which uses uniform particles as seeds that are swollen with monomers prior to conducting polymerization. The other method is dispersion polymerization, which is generally recognized as a type of precipitation polymerization conducted in the presence of a suitable

polymeric stabilizer that is soluble in the reaction medium. Under favorable circumstances dispersion polymerization, in a batch step process, results in the preparation of polymeric particles, often mono-disperse particles, of 0.1-15 μm in diameter.

Dispersion polymerization was initially developed employing a hydrocarbon medium in the 1970's [see, Barrett, K. E. J.; Thomas, H. R. *J. Polym. Sci., Polym. Chem. Ed.* **1969**, *7*, 2621]; however it was an extension of the procedure to encompass polar solvents, such as ethanol or methanol, that greatly expanded the utility of this polymerization procedure [see, Tseng, C. M.; Lu, Y. Y.; El-Aasser, M. S.; Vanderhoff, J. W. *J. Polym. Sci., Part A: Polym. Chem.* **1986**, *24*, 2995]. El-Asser later extended the procedure to living anionic dispersion polymerization in hydrocarbon solvents [see, El-Aasser, M. S.; et. al. *J. Polym. Sci., Part A: Polym. Chem.*, **1996**, *34*, 2633].

A dispersion polymerization is defined as a type of precipitation polymerization in which the monomer and all other reactants (including polymeric stabilizers) are initially soluble in the reaction medium, but the polymer is insoluble or substantially insoluble. Therefore a dispersion polymerization starts as a homogeneous solution polymerization but as polymer (or oligomer) chains grow in size they eventually reach a molecular weight higher than a certain critical value and precipitate from solution and aggregate to form colloidally unstable precursor particles. These particles coalesce and adsorb stabilizers from the reaction medium onto their surface until they become a colloidally stable dispersion of micelles in the reaction medium. At this point, the total number of particles in the system is fixed, and the nucleation stage ceases. Subsequent polymerization, also termed the particle growth stage, occurs predominantly inside the swollen nuclei or micelles but also in the reaction medium. However, the newly-formed polymers should not form additional nuclei but should be captured by existing particles [see, Kawaguchi, S.; Ito, K.; *Adv. Polym. Sci.*, **2005**, *175*, 299].

The reaction is easy to carry out, lends itself to scale up and yields particles with a very narrow and uniform particle size.

BRIEF SUMMARY

The present disclosure provides for a process for preparing substantially uniform-sized functional (co)polymer particles which utilizes a free radical polymerization process followed by a living or controlled radical polymerization process.

In one embodiment, the present disclosure provides a process for preparing

substantially uniform-sized functional (co)polymer particles. The process comprises polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a reaction medium comprising a stabilizer and a non-aqueous polar solvent in which the (co)polymer is substantially insoluble; forming a stable colloidal dispersion comprising the (co)polymer dispersed in substantially uniform-sized micelles in the reaction medium; adding precursors for a controlled radical (co)polymerization system; and polymerizing the remaining first radically (co)polymerizable monomer(s) by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles. In certain embodiments, the process may further comprising adding at least one additional radically (co)polymerizable monomer(s) after forming the stable colloidal dispersion.

According to other embodiments, the present disclosure provides for a continuous two-step batch dispersion polymerization process for the preparation of substantially uniform-sized functional polymer particles. The process comprises a first step comprising polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a stable colloidal dispersion and a second step comprising polymerizing the at least one first radically (co)polymerizable monomer(s) or an additional radically (co)polymerizable monomer(s) in the stable colloidal dispersion by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles.

BRIEF DESCRIPTION OF THE DRAWINGS

The various embodiments of the present disclosure may be better understood when read in conjunction with the following Figures in which:

Figures 1A, 1B and 1C illustrate scanning electron microscope (SEM) images of polystyrene particles prepared by conventional dispersion polymerization (Fig. 1A), one-batch ATRP (Fig. 1B), and one-batch reverse ATRP (Fig. 1C), respectively. The scale bars in the images represent 5 μm, 5 μm and 100 μm, respectively.

Figures 2A, 2B, 2C, and 2D illustrate SEM images of the polystyrene particle (Fig. 2A) prepared according to one exemplary set of conditions under the present disclosure; the polymerization kinetics (Fig. 2B); GPC traces of the obtained polymers during the polymerization process (Fig. 2C); and molecular weight evolution with monomer conversion

(Fig. 2D); respectively. The scale bar in Fig. 2A represents 5 μm.

Figures 3A, 3B, 3C, and 3D illustrate the molecular weight evolutions (Figs. 3A and 3B) and SEM images of polystyrene (PS) particles (Figs. 3C and 3D) prepared by two embodiments of the two-stage atom transfer radical dispersion polymerization process of the present disclosure. The scale bars in the images represent 5 μm.

Figures 4A, 4B, and 4C illustrate SEM images of crosslinked PS particles prepared by two embodiments of the two-stage atom transfer radical dispersion polymerization at 8 h with monomer conversion 26% (Fig. 4A) and 24 h with monomer conversion 95% (Figs. 4B and 4C), respectively. The scale bars in the images represent 5 μm, 5 μm and 2 μm, respectively.

Figures 5A, 5B, 5C, 5D, and 5E illustrate SEM images showing variation in size of particles produced by various embodiments of the two-stage ATDP process as targeted degree of polymerization is reduced. The scale bars in the images represent 5 μm.

Figures 6A and 6B illustrate SEM images showing the particle size in dispersion polymerization of methyl methacrylate (MMA). Fig. 6A illustrates a free radical polymerization and Fig. 6B illustrates particles prepared by ATDP. The scale bars in the images represent 5 μm.

Figures 7A and 7B illustrate SEM images of poly-2-hydroxyethyl methacrylate (pHEMA)-modified crosslinked polystyrene particles. The scale bars represent 5 μm and 2 μm, respectively.

DETAILED DESCRIPTION

In dispersion polymerization processes, it has been widely accepted that the key issue for preparation of uniformly sized colloidal particles is a short nucleation stage [see, LaMer, V. K.; Dinegar, R. H. *J. Am. Chem. Soc.*, **1950**, *72*, 4847]. The particle number and particle number distribution are determined during the nucleation stage and no secondary particles or coagulum should be formed during the particle growth stage. A prolonged nucleation stage usually results in a broad particle size distribution.

Use of "Living" or Controlled Radical Polymerization (CRP) processes has not been successfully applied to a dispersion-type polymerization to form substantially uniform-sized functional (co)polymer particles. As used herein, the term "substantially uniform-sized" when used with reference to the size of the (co)polymer particles means that the (co)polymer particles have a size that varies by less than 10%, in certain embodiments less than 5%, and

in specific embodiments less than 3%, when the diameters of more than 100 particles are measured. However, in a CRP, because all chains grow at the same rate, the time required for the preparation of a polymer with a molecular weight above the critical molecular weight of the reaction medium (i.e., the weight were the dispersion forms) is significantly longer than that in a FRP. Thus, this slower controlled radical polymerization process directly influences, most likely extends, the nucleation stage in a dispersion polymerization such that non-uniform particles are formed.

Furthermore, the nucleation stage in dispersion polymerization is very sensitive to variations in reaction components or conditions. It has been found that incorporation of functional monomers [Yang, W.; Yang, D.; Hu, J.; Wang, C.; Fu, S. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 555] or crosslinking agents [Song, J.-S.; Tronc, F.; Winnik, M. A. *J. Am. Chem. Soc.* **2004**, *126*, 6562; Song, J.-S.; Winnik, M. A. *Macromolecules* **2005**, *38*, 8300] in a standard free radical dispersion polymerization is much more difficult than that in other heterogeneous polymerizations such as emulsion polymerization.

In recent years several living/controlled radical polymerization (CRP) techniques, which encompass (co)polymerization of a wide range of monomers in a spectrum of reaction media, have been developed. The development of a living/controlled radical dispersion polymerization would be a way to expand both the design and scope of functional polymer colloids. Combining dispersion polymerization and CRP offers several potential benefits in addition to the preparation of uniform micron-sized particles. For example, particles prepared by CRP techniques contain polymers with pre-determined chain-end functionality; therefore they are suitable materials for *in situ,* or for post-polymerization, modification of the particles forming materials that could be tailored for a spectrum of applications.

Since the particles obtained from a CRP can be designed to contain tele-functional lower molecular weight polymers that can be swollen by solvents or additional monomers, they are ideal materials for use as seeds for a seeded polymerization or for the preparation of higher molecular weight materials or segmented copolymer particles. Therefore, in principle, when CRP is applied to a dispersion polymerization, all chains are initiated quickly and grow simultaneously therefore uniform particle growth and good control over particle size would be anticipated from a living/controlled dispersion polymerization.

However, in previous efforts to apply CRP techniques to dispersion polymerization problems were encountered. For example, when using nitroxide mediated polymerization

(NMP) [Hoelderle, M.; Baumert, M.; Muelhaupt, R. *Macromolecules* **1997**, *30*, 3420; Gabaston, L. I.; Jackson, R. A.; Armes, S. P. *Macromolecules* **1998**, *31*, 2883], degenerative transfer (DT) polymerization [Song, J.-S.; Winnik, M. A. *Macromolecules* **2006**, *39*, 8318-8325], and reversible addition-fragmentation transfer (RAFT) polymerization [Shim, S. E.; Jung, H.; Lee, H.; Biswas, J.; Choe, S. *Polymer* **2003**, *44*, 5563] as the CRP processes, polymers with controlled molecular weight and sufficient chain-end functionality have generally been obtained, however, particle size distribution was broad.

Furthermore, it was discovered that particle size uniformity, as well as the colloidal stability, declined as more radical control regulators (e.g. 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), DT, or RAFT agents) were added to the system. Particle size distribution was also broad in a recent PCT patent application, WO/2008/009997 [See, Figure 1], disclosing dispersion polymerization employing a RAFT agent, even though a narrow particle size was claimed.

Therefore there is a need for a controlled radical polymerization process that can prepare uniform-sized polymer beads with particle size control and narrow size distribution that further allows retention of functionality suitable for post-polymerization modification of the particle surface.

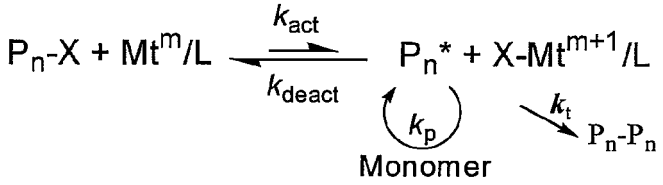
This need is met with the disclosed adaptation of atom transfer radical polymerization (ATRP) to a dispersion polymerization system which involves a continuous two-step batch polymerization process wherein the first step comprises conducting a standard free radical polymerization of radically (co)polymerizable monomer(s) and the second step comprises an ATRP process.

As noted above, addition of control agents for a controlled polymerization process affects the nucleation process. We can confirm the sensitivity of the nucleation process to reaction components based on our initial attempts to combine atom transfer radical polymerization (ATRP) and dispersion polymerization. Mono-disperse particles could not be achieved in a single batch mode polymerization.

ATRP has been described in a series of patents and patent applications with Matyjaszewski as co-inventor and Carnegie Mellon University as assignee, including: U.S. Patent Nos. 5,763,548; 5,807,937; 5,789,487; 5,945,491; 6,111,022; 6,121,371; 6,124,411; 6,162,882; 6,407,187; 6,512,060; 6,538,091; 6,541,580; 6,624,262; 6,624,263; 6,627,314; 6,790,919; 6,759,491; 6,887,962; 7,019,082; 7,056,455; 7,064,166; 7,125,938; 7,157,530; and 7,332,550 and U.S. and International PCT Patent Application Serial Nos. 09/534,827;

09/972,056; 10/034,908; 10/269,556; 10/289,545; 10/638,584; 10/860,807; 10/684,137; 10/781,061, 10/992,249 11/ 059,217; 10/ 887,029; 11/ 430,216; 10/548,354; 11/593,185; PCT/US05/07264, PCT/US05/07265, and PCT/US06/33792, all of which are herein incorporated by reference, for example, to define which monomers can be (co)polymerized in an ATRP process and which ligands should be selected to provide stable active transition metal complexes in various media. ATRP has also been discussed in numerous publications and reviewed in several book chapters [see, *ACS Symp. Ser.*, **1998**, *685*; *ACS Symp. Ser.*, **2000**; *768; Chem. Rev.* **2001**, *101*, 2921-2990; *ACS Symp. Ser.*, **2003**; *854*; *ACS Symp. Ser.*, **2006**; *944*], the disclosures of which are incorporated in their entirety by reference herein. Within these published articles and book chapters similar polymerization systems employing of forming the four essential components required for an ATRP (Scheme 1) may be referred to by different names, such as transition metal mediated polymerization or atom transfer polymerization, but the processes are similar and referred to herein as "ATRP".

Any patent, publication, or other disclosure material, in whole or in part, that is said to be incorporated by reference herein is incorporated herein only to the extent that the incorporated material does not conflict with existing definitions, statements, or other disclosure material set forth in this disclosure. As such, and to the extent necessary, the disclosure as set forth herein supersedes any conflicting material incorporated herein by reference. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosure material set forth herein will only be incorporated to the extent that no conflict arises between that incorporated material and the existing disclosure material.



Scheme 1: *Typical schematic of an ATRP equilibrium showing the four essential components: a transition metal that forms a stable complex with a ligand that exists in a lower (activator state) and higher (deactivator state) oxidation state to polymerize one or more radically (co)polymerizable monomer(s) wherein the majority of the chains are present in a dormant state comprising a transferable atom or group.*

It should be understood that any numerical range recited herein is intended to include all sub-ranges subsumed therein. For example, a range of "1 to 10" is intended to include all sub-ranges between (and including) the recited minimum value of 1 and the recited maximum value of 10, that is, having a minimum value equal to or greater than 1 and a maximum value of less than or equal to 10.

When a normal ATRP process was used for a dispersion polymerization, i.e. when Cu(I) species were added as the activators, nucleation (turbidity of the reaction system) was observed ~15 minutes after injection of ATRP initiators. This is visibly later than that in a conventional radical dispersion polymerization, in which nucleation occurred after ~5 min. under the similar reaction conditions.

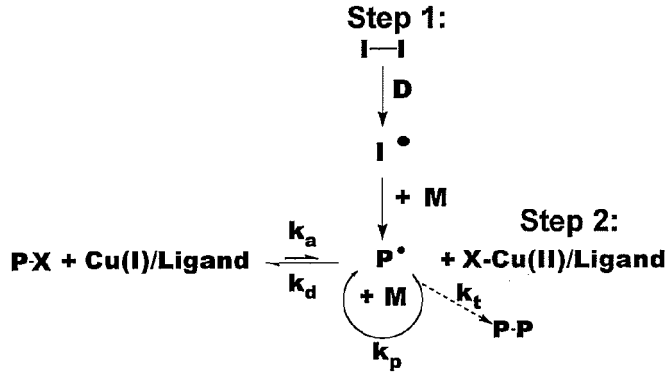
When a reverse ATRP was used, i.e. ATRP deactivators species, Cu(II), were added together with a conventional radical initiator, such as AIBN, the observed nucleation was postponed even more.

The SEM images of polystyrene particles prepared in single step dispersion polymerizations using free radical polymerization (FRP), normal ATRP, and reverse ATRP are shown in Figure 1. Comparing Figure 1A with 1B and 1C, it is clear that particle size distribution broadened to a significant degree with the involvement of the components of an ATRP process in the reaction media, regardless of using direct or reverse ATRP initiation/activation. The presence of particles with a broad distribution of particle size, i.e., small and exceptionally large particles, indicates that both an extended initial nucleation stage and secondary nucleation (i.e., nuclei formed after the first nucleation stage) had occurred.

It is believed that in a CRP because all chains grow at the same rate, the time required for the preparation a polymer with a molecular weight above the critical precipitating molecular weight is significantly longer than that of a standard FRP, where high molecular weight polymer is formed almost immediately. This slower controlled polymerization process directly influences, most likely extends, the nucleation stage in a dispersion polymerization since the slow growing oligo/polymeric species take a longer time to attain a molecular weight above the critical value.

A successful dispersion polymerization requires that one shorten the nucleation stage in order to provide mono-disperse polymeric particles. It was determined that an ATRP system, such as a reverse ATRP system, could be modified to a two-step process to allow an uncontrolled free radical polymerization to occur to the extent required to seed the system

(i.e., the nucleation step) prior to adding the reagents required for a controlled ATRP (see Scheme 2). The resulting two-step atom transfer dispersion polymerization provides substantially uniform-sized functional (co)polymer particles having well defined degree of polymerization, not previously accessible by FRP or CRP dispersion polymerization processes.



Scheme 2: *"Two-stage" atom transfer dispersion polymerization*

One difference between the initiation systems described in the present disclosure from that of a "classic" reverse ATRP is that the deactivator, the transition metal complex in its higher oxidation state, is added to the reaction at a certain time (~45 min) after the FRP polymerization was initiated. In this way, the first stage of the polymerization involves a standard FRP forming high molecular weight polymer, which should result in a short and clean nucleation stage, and improved uniformity in the size of the particles. In certain embodiments, the FRP polymerization for the nucleation step is allowed to proceed to less than 10% polymerization. In other embodiments, polymerization conversion after the nucleation period is complete in between 1% and 5% and continuing the polymerization to higher conversions leads to more stable particles.

The present disclosure describes several different features and aspects of the various exemplary embodiments provided herein. It is understood, however, that the present disclosure embraces numerous alternative embodiments, which may be accomplished by combining any of the different features, aspects, and embodiments described herein in any combination that one of ordinary skill in the art would find useful.

In the examples discussed below conversion in the first stage was less than 10% in order to ensure that the majority of the polymer chains retained an active chain end. Indeed in the examples, conversion of initially added monomers to polymer by FRP during nucleation was actually below ~3% when the copper complex was added to initiate the

reverse ATRP reaction. In this manner the second stage should be an ATRP, during which time the polymers produced should exhibit the characteristics of a living/controlled polymerization process, i.e., pre-determinable molecular weight, narrow polydispersity, and retention of chain end functionality

This novel *in situ* continuous batch two-stage reverse ATRP strategy efficiently resolved the problem of particle size uniformity. As seen in Figure 2A, the particles formed in such a procedure had very narrow size distribution. In addition, comparing Figure 1A and Figure 2A, it can be seen that the particles prepared from free radical dispersion polymerization (Fig. 1A) and the new continuous two-step atom transfer radical dispersion polymerization (ATDP, Fig. 2A) have very similar particle size (1.50 ± 0.05 μm and 1.54 ± 0.05 μm, respectively). While not intending to be limited by any interpretation, this can be considered as proof that the nucleation stage was complete before addition of ATRP deactivators and the *in situ* formation of the dormant polymer chains and the lower oxidation state transition metal activator complex. According to this embodiment, the initiation system was still a reverse ATRP. A critical difference between the initiation systems applied and demonstrated for the first time in this research from that of a classic reverse ATRP is that the deactivator is added to the reaction at a certain time after the polymerization was initiated by a free radical initiator and after the nucleation procedure was complete.

Additional CRP initiation procedures developed for ATRP at Carnegie Mellon University, that also start with the oxidatively stable higher oxidation state catalyst complex, namely simultaneous reverse and normal initiation ATRP (SR&NI ATRP) [see, U.S. Patent No. 6,759,491] and initiator for continuous activator regeneration (ICAR ATRP) [see PCT Application No. PCT/US06/33792] would also work, since in both these advanced procedures a standard free radical initiator is employed as part of the activation or reactivation procedure. These two procedures employ lower concentrations of the transition metal catalyst than a standard reverse ATRP and allow addition of an ATRP (macro)initiator to control the topology of the formed (co)polymer.

These procedures were also able to be modified to take into account the need to "seed" the dispersion polymerization prior to addition of the control agents. During the first stage the polymerization only involved a standard FRP forming a small fraction of high molecular weight polymer which should result in a short and clean nucleation stage, and improved uniformity in the size of the particles. After the nucleation stage is over, the

precursors for the CRP, for example, the ATRP deactivators, i.e. Cu(II) species, and ATRP (macro)initiators, are added to the polymerization. Therefore the second stage should be a well controlled ATRP process during which time the polymers produced should exhibit all the characteristics of a living and controlled polymerization process. The term (macro)initiators indicates that the added ATRP initiators comprise either a low molecular weight initiator species or a higher molecular weight macroinitiator species and that the added (macro)initiator can comprise one or more initiating atoms or groups. Indeed, since the macroinitiators only participate in the ATRP stage of the polymerization, they can optionally be added to the first stage and the catalyst complex added alone in the second stage to be activated and initiate the second controlled polymerization. In other embodiments, the ATRP (macro)initiators may be formed *in situ* by reaction of a radical species with the ATRP catalyst involving transfer of the radically transferable atom or group from the transition metal catalyst to the radical.

The rate of an ATDP can be considerably slower than a conventional radical dispersion polymerization because of the addition and retention of ATRP deactivators during the second stage. For example in the ATDP's reported herein, the molecular weight of the polymers formed in the controlled polymerization steadily shifted towards higher value, demonstrating the retention of active chain-end functionality during the polymerization. The weight fraction of polymers formed during the first stage FRP nucleation process, became insignificant in the final polymer particles, as evidenced by the inconsequential fraction of the FRP polymer peak in the final GPC trace (see, Figure 2C). The GPC trace of the final polymer formed during the reverse ATDP had tailing towards the low-MW area, which can be attributed to the slow decomposition of AIBN continuously forming new chains. The obtained polymer particles comprise polymers having a well defined molecular weight ~21,400 g/mol and relatively narrow polydispersity (M_w/M_n = 1.6) characteristic of a CRP, compared with M_w/M_n = 4-5 from conventional dispersion polymerization. Such tailing would be reduced in SR&NI ATDP and ICAR ATDP procedures and products with narrow or controlled PDI would be prepared since lower concentrations of free radical initiator are required.

In the initial standard reverse ATDP, the theoretical number-average molecular weight ($M_{n(theo)}$) was calculated based on the equation:

$$M_{n(theo)} = \frac{\Delta[M]}{2 \times f \times [AIBN]_0} M_m$$

in which f is the initiation efficiency of AIBN, which was assumed to be 75%, and M_m refers to the molecular weight of the monomer. The initiation efficiency of this system is reflected in the ratio of experimental molecular weight to theoretical molecular weight. It was calculated to be ~70% (Figure 2D).

The poor initiation efficiency may likely be due to:

1) an overestimated efficiency of the radicals formed by the decomposition of AIBN to initiate chain growth, and/or

2) coupling of oligomers in the initial stage of the ATRP, which reduces the number of living chains.

A lower concentration of free radical initiator should assist in attaining higher initiation efficiency, as indicated by the experiment targeting a higher degree of polymerization (DP_{target}).

Figures 3A and 3B show evolution of molecular weight of the two systems with DP_{target} of 100 and 260. It can be seen in the latter case that the initiation efficiency was very close to 100% while the procedure targeting a lower DP_{target}, of 100, resulted in initiation efficiency as low as ~53%. As the DP_{target} decreased, i.e., the initiator concentration increased, the particle size increased (Figure 3C and 3D). This is a consequence of the higher initiator concentration which results in a higher concentration of growing oligo/polymers and a rate of the polymerization which was faster than the adsorption rate of the stabilizer. Therefore the oligo/polymers tended to aggregate and form larger nuclei before sufficient stabilizers were able to be adsorbed onto the particles to stabilize them. Therefore larger particles were obtained. This observation was confirmed when higher DP's of polymerization were targeted e.g. target DP of 530 resulted in a slower rate of initiator decomposition and the formation of particles with a size = 1.17 μm.

In one embodiment of the present disclosure, this provides a procedure for preparation of larger particles with higher controllable molecular weight. In the initial stage conditions are selected to produce a lower DP_{target}, then once stable particles are formed and the control agents added a second, third or even later a fourth, aliquot of monomer is added to increase DP_{target}. Particle size can also be modified by selecting a free radical initiator that

decomposes at a faster or slower rate at a given temperature.

Polymer particles with higher fractions of functional polymer chains arising from added ATRP initiator can be attained using SR&NI or ICAR. Indeed a modified activator regeneration by electron transfer ATRP (ARGET ATRP) procedure can also be applied. In this embodiment, the amount and composition of the free radical initiator is selected to allow for the preparation of stable particles in a rapid nucleation procedure but allow subsequent reactivation of the higher oxidation state ATRP catalyst complex by action of a reducing agent [see, PCT/US06/33792].

In a further embodiment of the present disclosure, this sequential addition of monomers can be employed to prepare block copolymers or blocky-gradient copolymers, if some of the first monomer is present when the second monomer is added [see, Min, K. et al. "Development of an *ab Initio* Emulsion Atom Transfer Radical Polymerization: From Microemulsion to Emulsion." *J. Am. Chem. Soc.* **2006**, *128(32)*, 10521-10526; and PCT Int. Appl. WO 2007/025086 for a discussion of emulsion ATRP processes for forming block/blocky-gradient copolymers, the disclosures of which are incorporated in their entirety by reference herein].

As noted in the background section the preparation of uniform crosslinked particles by dispersion polymerization is an additional significant challenge because of the sensitivity of the nucleation stage to the presence of crosslinking agents. Song and Winnik et al. reported some success using the two-stage technique to incorporate crosslinking agents into polystyrene particles in a conventional free radical dispersion polymerization [*Macromolecules* **2005**, *38*, 8300]. However, the report pointed out that when DVB was used as the crosslinking agent, the rapid consumption of DVB into the crosslinked system resulted in a low swelling ability of the growing particles/nuclei with monomers and therefore irregular-shaped particles. Furthermore, particle coagulation was observed when the concentration of DVB is higher than a critical value even when using the two-stage technique. A dispersion polymerization in the presence of 1wt-% DVB resulted in severe coagulation after 2-3 hours. This phenomenon was also observed in our study (see, Table 2, run 2).

In order to overcome this limitation, we determined that it is advantageous to add fractions of the target amount of DVB multiple times. This novel stepwise addition of the comonomer responsible for crosslinking the particle resolved these stability problems in the disclosed CRP. In fact, using a periodic introduction of crosslinking agent can be beneficial

for incorporation of higher concentrations of crosslinking agents into the CRP crosslinked system produced by the two-stage ATDP process. Because the overall lifetime of a growing polymer chain in a CRP is significantly longer than in a standard free radical polymerization, due to repetitive activation-deactivation cycles, the polymer chains have more time to relax during their dormant period resulting in the synthesis of a more uniform crosslinked structure. Thus, particles with a uniform crosslinked structure should swell more efficiently in the monomer/solvent system and therefore they should have less stability problems. Furthermore since the uniform crosslinking network can be swollen by added monomers, subsequent multiple additions of monomers can increase the particle dimensions and/or the porosity and adsorption properties of the uniform crosslinked particle. Indeed, additional monomers or crosslinkers can be added in a continuous manner to the reaction.

In one embodiment of the invention, exemplifying crosslinked particles are successfully prepared by using a two-stage ATDP, in which 1 wt-% of the crosslinking agent was added together with the second fraction of monomers and solvents. The particles remained stable after 24 hours, with monomer conversion ~95%. By varying the overall ratio of added/formed ATRP initiators to crosslinking agents(i.e., I to XL) it is possible to prepare particles comprising polymers with structures that vary in architecture from soluble branched structures to densely crosslinked networks [see, PCT Application PCT/US07/21684 for a discussion of the transition between a soluble branched structure and crosslinked networks].

It is worth noting that polystyrene particles could only be clearly observed by SEM when the monomer conversion was higher than 50-60%. At low conversion the particles are so swollen with monomer and solvent that they form a film on the glass substrate and very soft, poorly defined SEM image would be anticipated. However, as Figure 4A shows, even at the low monomer conversion of 26%, the particles targeting a crosslinked structure were already clearly imaged indicating that divinylbenzene (DVB) had been incorporated into the particles. The surface morphology of the particles was rather smooth at low monomer conversion (Figure 4A), but became noticeably rougher when the conversion was higher (Figure 4B), which can be clearly seen at higher magnification in Figure 4C. Nevertheless, the particles remained spherical and mono-disperse through the end of polymerization. The crosslinked particles can be easily filtered from the solvent and re-dispersed in a second medium.

One advantage of carrying out ATRP for the preparation of crosslinked particles is

that the retained chain-end functionalities that can be directly used for further chain-extension and modification of the particle or particle surface. When using the particles from conventional dispersion polymerization processes, the initiators have to be further introduced and tethered to the accessible surfaces. This step can be avoided when using (co)polymer particles prepared directly by ATRP. It was envisioned that a sufficient number of accessible initiator functionalities should be available to allow the preparation of tethered copolymer chains providing functional surfaces in a porous particle or a functional tethered shell on a solid particle surface.

This embodiment of the process is exemplified by employing the first formed polystyrene particles as macroinitiators for chain-extension with 2-hydroxyethyl methacrylate (HEMA). Halide exchange technique was applied in this study considering the rate of cross-propagation from styryl radicals to methacrylate monomers. After the grafting from polymerization of HEMA, the particles can be dispersed in methanol, which indicates that the surface of the particles have been modified by successfully chain-extending accessible initiating functionality with poly(HEMA), since bare polystyrene particles cannot be dispersed in methanol. It can be seen from the SEM images that the surface of the modified polystyrene particles became smoother after p(HEMA) modification.

If the first formed crosslinked particles have been prepared in the presence of porogens to form crosslinked particles suitable for chromatographic applications then every accessible surface would have been modified in the grafting from (co)polymerization.

Therefore one embodiment of the invention an atom transfer radical dispersion polymerization is exemplified by the polymerization of styrene in ethanol which was successfully carried out using a continuous "two-stage" polymerization technique, in which the first stage involves a standard FRP and the second stage a reverse ATRP. Polystyrene particles with particle size of 1.5-2.5 μm were obtained. The particles prepared using the two-stage ATDP displayed narrow particle size distribution, contained polymers with molecular weight ~20,000 g/mol and relatively narrow, less than 2.0, polydispersity (M_w/M_n = 1.4-1.8, compared with M_w/M_n = 4-5 from conventional dispersion polymerization).

This novel ATDP technique also facilitated the preparation of uniform crosslinked particles wherein a crosslinkable monomer, such as a divinyl crosslinking agent, is added during the second or even in a third stage of the controlled polymerization process forming uniform particles. As a consequence of the involvement of ATRP and the option of addition

of the crosslinking agent at the same time as the active components of the ATRP process or even periodic addition of the crosslinking agent as the reaction progressed, the ATDP process provides controlled incorporation of the crosslinking agent to form substantially uniform-sized crosslinked particles.

In addition, these crosslinked particles were successfully chain-extended with a second functional monomer, exemplified herein by HEMA, indicating well-retained accessible chain-end functionality on the accessible surface of the particles for further modification of particle surfaces thereby forming a core/shell structure allowing uniform dispersion of the first formed particles in polar solvents such as water and methanol, thereby exemplifying that the monomer(s) selected for the shell/surface polymerization can be selected to incorporate a desired functionality into the uniform particle.

Polymer particles of dimensions obtained from this process are finding an increasing number of applications in coatings, electronics, microelectronics, biomedical, and information technology. Particle size control and narrow size distribution are key parameters for most of these applications.

According to one embodiment, the present disclosure provides a process for preparing substantially uniform-sized functional (co)polymer particles. The process comprises polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a reaction medium comprising a stabilizer and a non-aqueous polar solvent in which the (co)polymer is substantially insoluble; forming a stable colloidal dispersion comprising the (co)polymer dispersed in substantially uniform-sized micelles in the reaction medium; adding precursors for a controlled radical (co)polymerization system; and polymerizing the remaining first radically (co)polymerizable monomer(s) by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles.

As described herein, polymerizing the at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer occurs in a first step of the ATDP process described herein. During this nucleation step, the formed (co)polymer is substantially insoluble in the non-aqueous polar solvent and, in the presence of stabilizers and optionally one or more co-stabilizer, forms a stable colloidal dispersion comprising the (co)polymer dispersed in substantially uniform-sized micelles in the reaction medium. Suitable stabilizers and co-stabilizers include surfactants, such as polymeric

surfactants, nonionic surfactants, anionic surfactants, cationic surfactants, such as, but not limited to poly(N-vinylpyrrolidone) (PVP) and the TRITON® line of surfactants.

In certain embodiments, polymerizing the at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process occurs in a system initially comprising the stabilizer, a free radical initiator, the at least one first radically (co)polymerizable monomer(s), a non-aqueous polar solvent, and optionally the co-stabilizer. According to certain embodiments, the initial particle size, which may be determined by the size of the micelle formed during the nucleation, is controlled by an initial ratio of the free radical initiator to the concentration of the at least one radically (co)polymerizable monomer(s). Suitable free radical initiators include free radical initiators commonly used to initiate free radical polymerization reactions, such as, but not limited to peroxides and 2,2'-azobisisobutyronitrile (AIBN). Suitable free radical (co)polymerizable monomers include those commonly used in FRP type processes and known to those skilled in the art. Suitable non-aqueous polar solvents include, for example, but are not limited to, alcohols such as methanol, ethanol, propanol, and butanol.

In other specific embodiments, the solvent may additionally comprise a porogen. According to these embodiments, the resulting substantially uniform-sized functional (co)polymer particles may be porous particles.

In certain embodiments, the FRP nucleation process comprises initiating the polymerization in the presence of all of the at least one first radically (co)polymerizable monomer(s), whereas in other embodiments, only a portion of the at least one first radically (co)polymerizable monomer(s) are present in the solution when the FRP is initiated. For example, in specific embodiments, less than 10% of the at least one first radically (co)polymerizable monomer(s) may be polymerized by the FRP. In other embodiments, from 1% to 5% of the at least one first radically (co)polymerizable monomer(s) may be polymerized by the FRP during the first step. As will be understood by one having skill in the art reading on the present disclosure, the extent of the FRP polymerization process may be determined by tailoring the reactivity of the FRP system or by the timing of the adding of the precursors for the controlled radical (co)polymerization system. For example, the precursors of the CRP may be added after free radical polymerization of less than 10% of the at least one first radically (co)polymerizable monomer(s) or after free radical polymerization of from 1% to 5% of the at least one first radically (co)polymerizable monomer(s).

According to certain embodiments, the processes of the present disclosures may further comprise adding at least one additional radically (co)polymerizable monomer(s) to the reaction after forming the stable colloidal dispersion and/or after adding the precursors for the controlled radical (co)polymerization. In these embodiments, the additional monomer(s) may migrate to the micelles and participate in the ATRP step of the two-stage process. In certain embodiment, the least one additional radically (co)polymerizable monomer(s) may be the same as the at least one first radically (co)polymerizable monomer(s). In these embodiments, the additional monomers may be incorporated into a homopolymer structure. In other embodiments, the least one additional radically (co)polymerizable monomer(s) may be the different from the at least one first radically (co)polymerizable monomer(s). In these embodiments, the resulting copolymers may be gradient, block, or blocky-gradient copolymers. For example, in certain embodiments adding the additional radically (co)polymerizable monomers may comprise one of adding the additional radically (co)polymerizable monomer(s) in a continuous manner and adding the additional radically (co)polymerizable monomer(s) in multiple addition stages.

Further, in other embodiments, the process may further comprise adding one or more additional amounts of a radically (co)polymerizable monomer(s) (which may be the same or different from the at least one first radically (co)polymerizable monomer(s) and/or the at least one additional radically (co)polymerizable (co)monomer(s)) to the process to continue the CRP process after polymerizing the additional radically (co)polymerizable monomer(s) by the CRP process. Thus, a multistage process may result in copolymers with well defined block structure, MW and degree of polymerization may be synthesized by the disclosed ATDP process. These embodiments take advantage of the capability of ATRP processes to control copolymer structure by selection of monomer structure. For example, in one embodiment, adding the one or more additional amounts of a radically (co)polymerizable monomer(s) may increase the degree of polymerization of the polymers in the particles by continuing the polymerization process. In certain embodiments, this allows control of the particle size (diameter), resulting in final particles with a larger or increased uniform sizes. In other embodiments, the characteristics of the polymer structure of the surface of the particle may be tailored by selection of the time of addition of and/or functionality of monomer units to control specific characteristics of the particle such as swelling, solubility and the like.

As recited herein, the second-step of the disclosed ATDP process comprises adding precursors for the controlled radical (co)polymerization system and polymerizing remaining

first radically (co)polymerizable monomers by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles. According to various embodiments, the controlled radical (co)polymerization process may be selected from atom transfer radical polymerization processes, including an initiation procedure comprising standard ATRP, reverse ATRP, simultaneous reverse and normal initiation ATRP (SR&NI ATRP), initiator for continuous activator regeneration ATRP (ICAR ATRP), and activator regeneration by electron transfer ATRP (ARGET ATRP). The various components of suitable precursor systems and initiation procedures for these ATRP processes are described in previous ATRP based patents by Matyjaszewski et al. For example, according to one embodiment, adding the precursors for the controlled radical (co)polymerization system may comprise adding a transition metal in a higher oxidation state comprising a radically transferable atom or group and a ligand that forms a complex with the transition metal. According to specific embodiments, the ligand/transition metal complex may be soluble in the substantially uniform-sized micelles in the reaction medium (solvent/monomer), such that the ligand/transition metal complex may migrate to the micelle. Once in the micelle, the ATRP polymerization of the remaining first radically (co)polymerizable monomer(s) and/or any additionally added radically (co)polymerizable monomer(s) may be initiated.

As described herein, certain embodiments of the presently disclosed processes may further comprise adding at least one cross-linkable monomer. According to these embodiments, the cross-linkable monomer may be incorporated into the copolymer structure and form cross-links between the developing polymer chains. These cross-links may then impart desired characteristics to the resulting copolymer particles. According to one embodiment, the at least one cross-linkable monomer may be added in a continuous manner in order to incorporate the targeted level of crosslinking units into the particle without inducing particle aggregation. In other embodiments the at least one cross-linkable monomer may be added in multiple addition stages. Specific examples of suitable cross-linkable monomers include radically cross polymerizable monomers having two or more radically reactive groups such as a plurality of carbon-carbon double or triple bonds. For example, in certain embodiments, the cross-linkable monomer may comprise a polyvinyl monomer, such as a divinyl monomer (for example, divinylbenzene (DVB)).

In specific embodiments of the disclosed dispersion polymerization process, the process may further comprise separating the substantially uniform-sized functional (co)polymer particles from the reaction medium and submitting the substantially uniform-

sized (co)polymer particles to an atom transfer radical suspension polymerization process, wherein the substantially uniform-sized (co)polymer particles are used as a multifunctional macroinitiator for the ATRP process. This embodiment takes advantage of the fact that the (co)polymer particles formed by the ATDP process will have reactive functionality at the ends of the polymer chain ends (i.e., a transferable atom or group) that may react in further ATRP-type processes. Thus, the particles formed by the ATDP process disclosed herein may be further modified and/or functionalized by additional CRP processes or atom transfer radical addition (ATRA) processes.

According to the various embodiments of the present disclosure, the substantially uniform-sized functional (co)polymer particles formed by the disclosed two-step ATDP process may have an average particle size ranging from 0.1 μm to 15 μm. In other embodiments, the (co)polymer particles may have an average particle size ranging from 0.5 μm to 10 μm. However, one skilled in the art will recognize that particles having uniform-size but larger size (i.e., greater than 15 μm) may be synthesized utilizing the ATDP synthesized particles as macroinitiators with further functionalization of the surface reactive atoms or groups by further ATRP processes.

Other embodiments of the present disclosure provide a continuous two-step batch dispersion polymerization process for the preparation of substantially uniform-sized functional (co)polymer particles. The process comprises a first step comprising polymerizing at least one first radically(co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a stable colloidal dispersion; and a second step comprising polymerizing the at least one first radically (co)polymerizable monomer(s) or an additional radically (co)polymerizable monomer(s) in the stable colloidal dispersion by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles. As described herein, the stable colloidal dispersion may comprise the (co)polymer formed by the FRP process in substantially uniform-sized micelles dispersed in a reaction medium comprising a stabilizer and a non-aqueous polar solvent. Suitable initiation procedures for controlled radical (co)polymerization processes are described herein.

In specific embodiments, the second step of the two-step batch dispersion polymerization process may further comprise adding precursors for a controlled radically (co)polymerization system to the process. Suitable precursor systems are described herein. Other embodiments may further comprise adding one or more cross-linkable monomers, such

as a divinyl monomer, as set forth herein.

The various non-limiting embodiments of the present two-step atom transfer dispersion polymerization process described herein will be better understood when read in conjunction with the following non-limiting examples.

EXAMPLES

Materials.

All chemicals, including EBiB, bpy, CuBr, $CuBr_2$, poly(N-vinylpyrrolidone) (PVP, average $M_w \sim 55{,}000$), TRITON® X-305 (octylphenol ethoxylate, 70%) were purchased from Aldrich, Milwaukee, WI and were used as received unless otherwise stated. Styrene (99%) and divinylbenzene (DVB, 80%) were purified by passing through a column filled with basic aluminum oxide to remove inhibitor and/or antioxidant and was stored at -5 °C. 2,2'-Azobisisobutylronitrile (AIBN) was recrystallized in ethanol. Tripyridinemethyleneamine (TPMA) was synthesized according to the published procedures.

Example 1:

Comparator 1: Conventional radical dispersion polymerization.

A 50-mL Schlenk flask was charged with ethanol, styrene (and DVB, if preparing crosslinked particles), stabilizer PVP, co-stabilizer TRITON® X-305 and initiator AIBN. Detailed recipes are listed in Table 1. The resulting homogenous solution was deoxygenated by bubbling with nitrogen at room temperature for 30 min. The flask was then placed in a 70 °C oil bath and stirred with a magnetic stirrer at ~100 rpm. The polymerization was stopped after 24 hours by cooling the flask to room temperature.

Comparator 2: One-batch atom transfer dispersion polymerization of styrene.

The one-batch reactions were performed using the same procedure employed for the conventional radical dispersion polymerization, the only difference was addition of the components required for the ATRP together with the monomer and solvents. These examples provided particles with a broader distribution of particle size. The detailed recipes are listed in Table 1.

Example 1B:

In the two-stage experiments, all of the stabilizer (PVP), the co-stabilizer (TRITON®

X-305) and initiator (AIBN), and half of the monomer and ethanol were charged to a 50-mL Schlenk flask. The formed homogeneous solution was deoxygenated by bubbling nitrogen through the mixture at room temperature for 30 min. The flask was then placed in a 70 °C oil bath under magnetic stirring, ~100 rpm. $CuBr_2$ and TPMA were dissolved in a mixture of the remaining styrene and ethanol at 70 °C under nitrogen. This solution was added to the reaction after the polymerization had run for 45 min. Aliquots were withdrawn from the reaction at different time intervals to determine conversion by gravimetry. The samples were dried and dissolved in THF before being subjected to gel permeation chromatography (GPC) for molecular weight analysis. The polymerizations were stopped by exposing the catalysts to air.

Table 1. Process for the dispersion polymerizations of styrene in ethanol*

Run	Initiation	First Stage	Second Stage
		St_1: AIBN: $Ethanol_1$: $CuBr_2$/TPMA (g)	St_2: $Ethanol_2$: $CuBr_2$/TPMA (g)
1	FRP	3.28: 0.021: 11: 0	
2	One-batch direct ATRP	3.28: 0: 0.04(CuBr)/0.052: EBiB	
3	One-batch reverse ATRP	3.28: 0.021: 11: 0.04/ 0.052	
4	Two-stage ATRP	1.64: 0.021: 5.5 : 0	1.64: 5.5: 0.066/ 0.086
5	Two-stage ATRP	1.64: 0.034: 5.5: 0	1.64: 5.5: 0.105/ 0.137
6	Two-stage ATRP	1.64: 0.013: 5.5: 0	1.64: 5.5: 0.04/ 0.052

*PVP: 0.49 g, TRITON® X305: 0.13 g, polymerization temperature: 70 °C.

Characterization:

Monomer conversion was measured gravimetrically. Molecular weight and molecular weight distribution (M_w/M_n) were determined by GPC equipped with an autosampler (Waters, 717 plus), HPLC pump with THF as eluant at 1 mL/min (Waters, 515), and four columns (guard, 10^5 Å, 10^3 Å, and 100 Å; Polymer Standards Services) in series. Toluene was used as an internal standard. A calibration curve based on linear polystyrene standards was used in conjunction with a differential refractometer (Waters, 2410). Particle sizes and particle size distributions were examined by scanning electron microscopy (SEM, Hitachi S-2460N). SEM samples were prepared by drying a drop of diluted suspension on a clean microscope cover glass. The average particle size was based on measurement of 300 individual particles in the SEM images.

Example 2:

Further examples targeting different degrees of polymerization (DP) were conducted and the result from examination of various initiator concentrations was: the size of particles decreased as the amount of initiator decreased. See Figure 5. With a higher initial concentration of radicals the number of radicals present in the system increased and accordingly the rate of polymerization increased and the stabilizers were not able to quickly cover the surface of each proto-particle therefore the oligomers tended to aggregate and form larger nuclei and therefore larger particles are obtained. Similar reasoning would indicate that with a given initiator a larger particle size is also obtained at higher temperature.

Example 3: Atom Transfer Dispersion Polymerization of styrene and a crosslinker

Table 2 lists conditions for the copolymerization of a crosslinking agent with styrene.

Table 2. Crosslinked Particles*

Run	Initiation	First Stage	Second Stage
		St_1: AIBN: $Ethanol_1$: $CuBr_2$/TPMA (g)	St_2: $Ethanol_2$: $CuBr_2$/TPMA (g)
1	Two-stage FRP	1.64: 0.013: 6.3: 0	1.64: 6.3: 0 (0.03 g DVB)
2	Two-stage ATRP	1.64: 0.013: 6.3: 0	1.64: 6.3: 0.04/ 0.052 (0.03 g DVB)
3	Two-stage ATRP	1.64: 0.013: 6.3: 0	1.64: 6.3: 0.04/ 0.052 (0.05 g DVB)
4	Two-stage ATRP	1.64: 0.013: 6.3: 0	1.64: 6.3: 0.04/ 0.052 (0.05 g DVB)

*PVP: 0.49 g, TRITON® X-305: 0.13 g, polymerization temperature: 70 °C.

Runs 3 and 4 in Table 2 demonstrate the utility of adding fractions of the required amount of DVB multiple times to resolve these stability problems. Polystyrene particles were successfully prepared using a two-stage atom transfer radical dispersion polymerization, in which 1 wt-% DVB was added together with the second fraction of monomers and solvents. The particles remained stable after 24 hours, with monomer conversion ~95%. It is worth noting that the polystyrene particles can only be clearly observed in SEM when the monomer conversion was higher than 50-60%. At low conversion the particles are excessively swollen with monomer and solvent. They form a film on the glass substrate and a very soft SEM image would be anticipated. However, as Figure 4A shows, even at the low monomer conversion (26%), the crosslinked particles were already clearly imaged, indicating DVB has been incorporated into the particles. The surface morphology of the particles was

rather smooth at low monomer conversion (Figure 4A), but noticeably rougher when the conversion was higher (Figure 4B), which can be clearly seen with a high magnification in Figure 4C. This increase in surface roughness has been also observed when conventional dispersion polymerization was carried out in the presence of crosslinking agents. In the present study, the particles remained spherical and monodisperse till the end of polymerization. The crosslinked particles can be easily dispersed in THF.

Example 4: Chain extension of crosslinked polystyrene particles prepared by ATRP dispersion with 2-hydroxyethyl methacrylate (HEMA).

A direct ATRP of HEMA was carried out with crosslinked polystyrene particles as macroinitiators in DMF at 35 °C. The crosslinked polystyrene particles were synthesized in a two-stage atom transfer radical dispersion copolymerization, and were separated from the ethanol suspension medium by centrifugation (5000 rpm, 20 min). The particles were washed with THF to remove any remaining monomer and dried under vacuum. A dispersion of the particles (0.2 g) in DMF (3.6 mL) was mixed with HEMA monomer (1.44 mL), and bpy (0.0185 g) then the mixture was subjected to five cycles of freeze-pump-thaw to remove oxygen. The reaction flask was then back-filled with nitrogen and CuCl (0.0056 g), $CuCl_2$ (0.0004 g) were added to the frozen mixture. The flask was sealed again and subject to vacuum followed by back-filling with nitrogen. The reaction flask was then placed in a 35 °C oil bath to conduct the polymerization. The polymerization was stopped after 40 hours by exposing the reaction mixture to air. The products were separated by centrifugation (5000 rpm, 20 min) and washed by methanol for several times.

Example 5: PMMA atom transfer dispersion polymerization.

MMA was also examined as a monomer for dispersion polymerization. It was determined that ethanol was not an appropriate dispersion medium for such system since PMMA has too high a solubility in ethanol. Thus methanol was selected. PVP was still used as stabilizer and no co-stabilizer was used in this system.

A free radical polymerization was first attempted. The rate of the polymerization was close to a 1st order reaction, however, the polymer showed a typical trend of molecular weight evolvement as in a free radical polymerization, and a broadening of MWD as conversion increased.

Two-step ATDP was then applied in this system. The kinetic plot looked very similar to that in FRP but the rate polymerization was considerably slower because of the effect of

deactivation by Cu(II). The MWD of the obtained polymer was significantly narrower, close to 1.5.

Figure 6, shows the PMMA particles from FRP and ATRP. The particles formed by ATDP under this initial set of conditions displayed slightly broader particle size distribution, which implies secondary nucleation, i.e. the nucleation stage was not finished when the second part of monomer/solvent/ATRP catalysts were added. Therefore, to improve such size control, a further-delayed addition of the components required to conduct the second step would be beneficial or higher DP should be targeted.

CLAIMS

1. A process for preparing substantially uniform-sized functional (co)polymer particles comprising:

polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a reaction medium comprising a stabilizer and a non-aqueous polar solvent in which the (co)polymer is substantially insoluble;

forming a stable colloidal dispersion comprising the (co)polymer dispersed in substantially uniform-sized micelles in the reaction medium;

adding precursors for a controlled radical (co)polymerization system; and

polymerizing remaining first radically (co)polymerizable monomer(s) by a controlled radical (co)polymerization process for form substantially uniform-sized functional (co)polymer particles.

2. The process of claim 1, further comprising adding at least one additional radically (co)polymerizable monomer(s) after forming the stable colloidal dispersion.

3. The process of claim 2, wherein the at least one additional radically (co)polymerizable monomer(s) are the same as the at least one first radically (co)polymerizable monomer(s).

4. The process of claim 2, wherein the at least one additional radically (co)polymerizable monomer(s) are different from the at least one first radically (co)polymerizable monomer(s).

5. The process of any of claims 1-4, further comprising adding at least one cross-linkable monomer.

6. The process of claim 5, wherein adding the at least one cross-linkable monomer comprises one of adding the at least one cross-linkable monomer in a continuous manner and adding the at least one cross-linkable monomer in multiple addition stages.

7. The process of claim 5 or 6, wherein the at least one cross-linkable monomer

comprises a divinyl monomer.

8. The process of any of claims 1-7, wherein the controlled radical (co)polymerization process is an atom transfer radical polymerization (ATRP) with an initiation procedure selected from the group consisting of standard ATRP, reverse ATRP, simultaneous reverse and normal initiation ATRP (SR&NI ATRP), initiator for continuous activator regeneration ATRP (ICAR ATRP), and activators regenerated by electron transfer ATRP (ARGET ATRP).

9. The process of any of claims 1-8, wherein adding the precursors for the controlled radical (co)polymerization system comprises adding a transition metal in a higher oxidation state comprising a radically transferable atom or group and a ligand that forms a complex with the transition metal wherein the ligand/transition metal complex is soluble in the substantially uniform-sized micelles in the solvent.

10. The process of any of claims 1-9, wherein polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process occurs in a system initially comprising:

the stabilizer;

a free radical initiator;

the at least one first radically (co)polymerizable monomer(s);

the solvent; and

optionally a co-stabilizer.

11. The process of claim 10, wherein initial particle size is controlled by an initial ratio of the free radical initiator to the at least one first radically (co)polymerizable monomer(s).

12. The process of any of claims 1-11, wherein adding the additional radically (co)polymerizable monomer(s) comprises one of adding the additional radically (co)polymerizable monomer(s) in a continuous manner and adding the additional radically (co)polymerizable monomer(s) in multiple addition stages.

13. The process of any of claims 1-12, further comprising adding one or more additional amounts of a radically (co)polymerizable monomer(s) to the process to continue the

controlled radical (co)polymerization process after polymerizing the additional radically (co)polymerizable monomer(s) by the controlled radical (co)polymerization process.

14. The process of claim 13, wherein adding the one or more additional amounts of a radically (co)polymerizable monomer(s) increases at least one of a degree of polymerization of the polymers of the particle and a final particle size.

15. The process of claim 13 or 14, wherein adding the one or more additional amounts of a radically (co)polymerizable monomer(s) comprises adding one or more additional amounts of a radically (co)polymerizable monomer(s) different from at least one of the at least one first radically (co)polymerizable monomer(s) and the additional radically (co)polymerizable monomer(s).

16. The process of claim 15, wherein the substantially uniform-sized functional (co)polymer particles comprise block copolymer particles or blocky-gradient copolymer particles.

17. The process of any of claims 1-17, further comprising

separating the substantially uniform-sized functional (co)polymer particles from the medium; and

submitting the substantially uniform-sized functional (co)polymer particles to an atom transfer radical polymerization process, wherein the substantially uniform-sized functional (co)polymer particles are used as a multifunctional macroinitiator for the atom transfer radical polymerization process.

18. The process of any of claims 1-17, wherein the solvent additionally comprises a porogen.

19. The process of claim 18, wherein the substantially uniform-sized functional (co)polymer particles are porous particles.

20. The process of any of claims 1-19, wherein the precursors for the controlled radical (co)polymerization system are added to the process after polymerizing less than 10% of the at

least one first radically (co)polymerizable monomer(s) by the free radical (co)polymerization process.

21. The process of any of claims 1-19, wherein the precursors for the controlled radical (co)polymerization system are added to the process after polymerizing from 1% to 5% of the at least one first radically (co)polymerizable monomer(s) by the free radical (co)polymerization process.

22. The process of any of claims 1-21, wherein the substantially uniform-sized functional (co)polymer particles have an average particle size ranging from 0.1 μm to 15 μm.

23. A continuous two-step batch dispersion polymerization process for the preparation of substantially uniform-sized functional polymer particles comprising:

a first step comprising polymerizing at least one first radically (co)polymerizable monomer(s) by a free radical (co)polymerization process to form a (co)polymer in a stable colloidal dispersion; and

a second step comprising polymerizing the at least one first radically (co)polymerizable monomer(s) or an additional radically (co)polymerizable monomer(s) in the stable colloidal dispersion by a controlled radical (co)polymerization process to form substantially uniform-sized functional (co)polymer particles.

24. The process of claim 23, wherein the stable colloidal dispersion comprises the (co)polymer in substantially uniform-sized micelles dispersed in a medium comprising a stabilizer and a non-aqueous polar solvent.

25. The process of claim 23 or 24, wherein the controlled radical (co)polymerization process is an atom transfer radical polymerization (ATRP) with an initiation procedure selected from the group consisting of standard ATRP, reverse ATRP, simultaneous reverse and normal initiation ATRP (SR&NI ATRP), initiator for continuous activator regeneration ATRP (ICAR ATRP), and activators regenerated by electron transfer ATRP (ARGET ATRP).

26. The process of any of claims 23-25, wherein the second step further comprises adding precursors for a controlled radical (co)polymerization system to the process, the system

comprising:

a transition metal in a higher oxidation state comprising a radically transferable atom or group; and

a ligand that forms a complex with the transition metal,

wherein the ligand/transition metal complex is soluble in the substantially uniform-sized micelles.

27. The process of any of claims 23-26, further comprising:

adding a cross-linkable divinyl monomer.

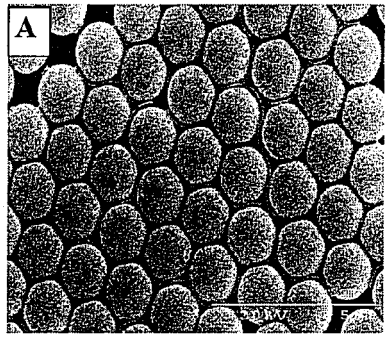


Fig. 1A

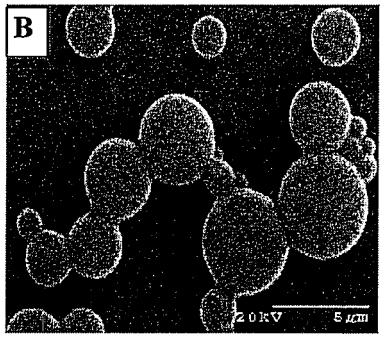


Fig. 1B

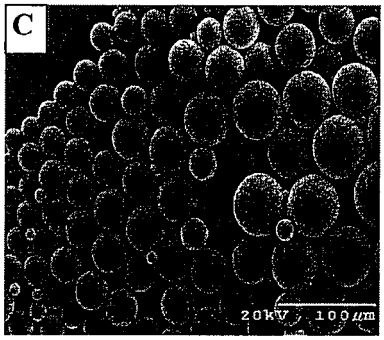


Fig. 1C

Fig. 2A

Fig. 2B

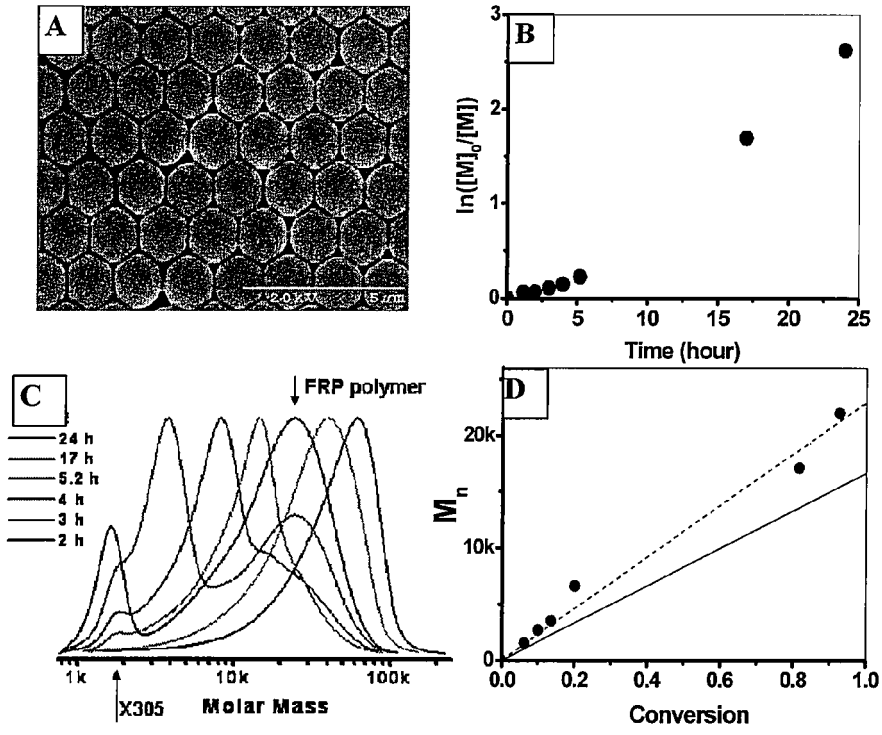


Fig. 2C

Fig. 2D

Fig. 3A

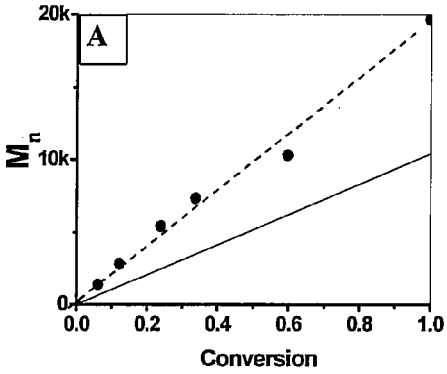
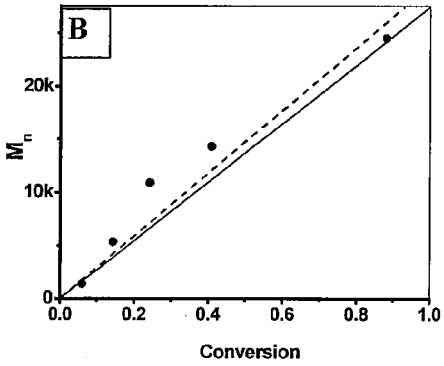


Fig. 3B



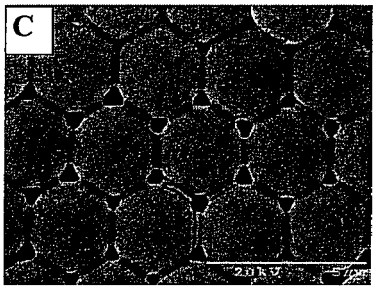


Fig. 3C

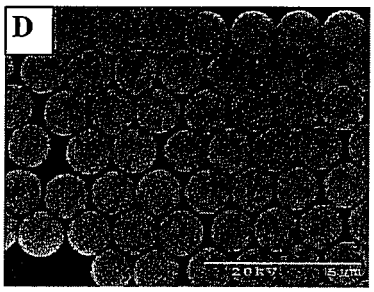


Fig. 3D

Fig. 4A

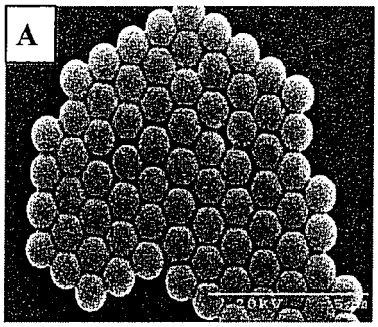


Fig. 4B

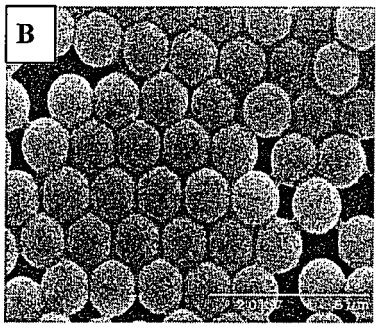


Fig. 4C

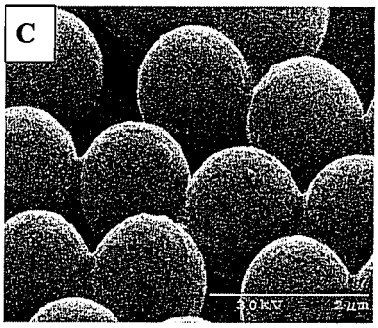


Fig. 5A (DP 530)

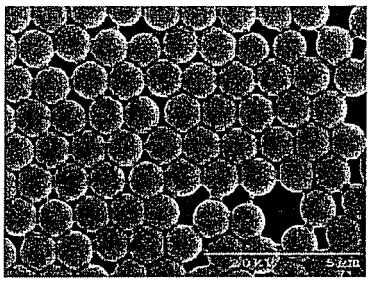


Fig. 5B (DP 265)

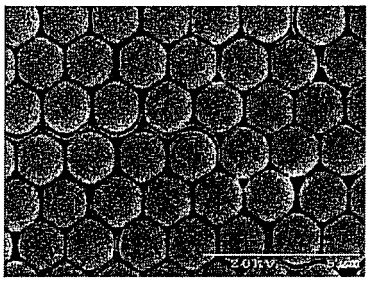


Fig. 5C (FRP, DP same as B)

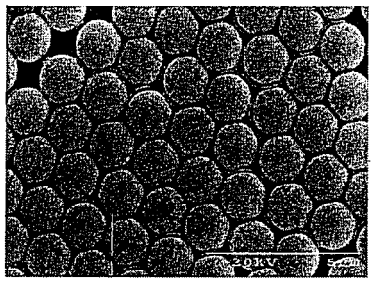


Fig. 5D (DP 160)

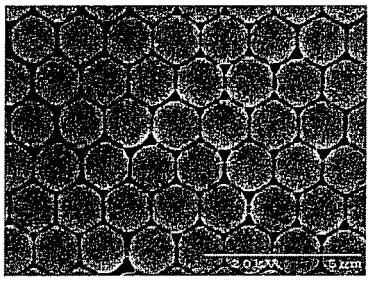


Fig. 5E (DP 100)

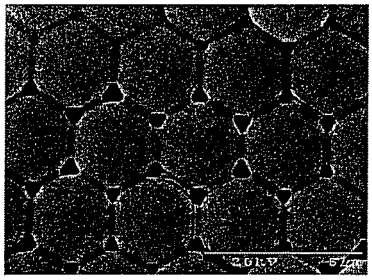


Fig. 6A

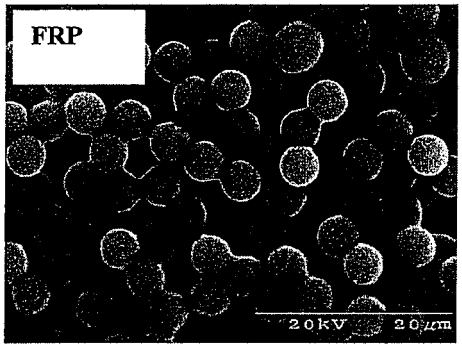


Fig. 6B

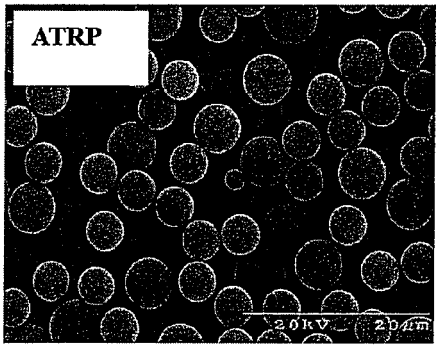


Fig. 7A

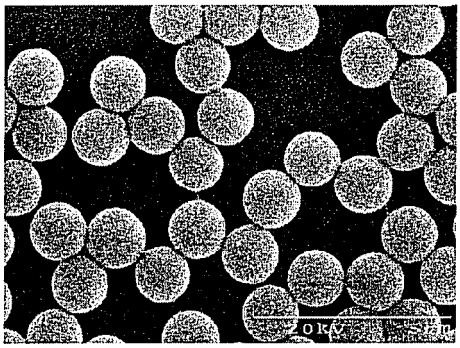
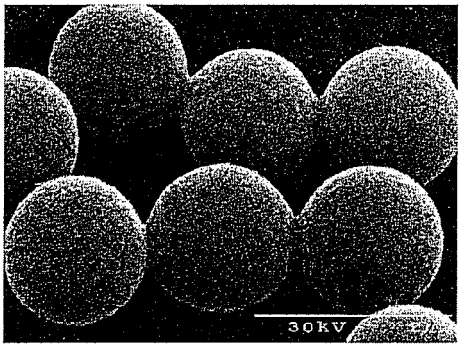


Fig. 7B



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/064710

A. CLASSIFICATION OF SUBJECT MATTER
INV. C08F12/08
ADD. C08F293/00 C08F2/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C08F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	19000101, 1 January 1900 (1900-01-01), XP009107440 page 302 page 306 page 316	1-27
A	WO 2007/025086 A (UNIV CARNEGIE MELLON [US]; MATYJASZEWSKI KRZYSZTOF [US]; MIN KE [US]) 1 March 2007 (2007-03-01) the whole document	1-27

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 October 2008	04/11/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gold, Josef

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/064710

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	KE MIN ET AL: "ATOM TRANSFER RADICAL DISPERISON POLYMERIZATION OF STYRENE IN ETHANOL" MACROMOLECULES, ACS, WASHINGTON, DC, US, vol. 40, no. 20, 2 October 2007 (2007-10-02), pages 7217-7222, XP001507473 ISSN: 0024-9297 page 7217 - page 7221	1-27
P,X	KE MIN ET AL: "Atom Transfer Radical Dispersion Polymerization of Styrene in Ethanol" POLYMER PREPRINTS, AMERICAN CHEMICAL SOCIETY, US, vol. 48, 23 July 2007 (2007-07-23), pages 260-261, XP009107489 ISSN: 0032-3934 page 260 - page 261	1-27

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2008/064710

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2007025086 A	01-03-2007	EP 1928919 A2	11-06-2008